Ocean Engineering 156 (2018) 564–579

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Dynamic reconfiguration of autonomous underwater vehicles propulsion system using genetic optimization

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ARTICLE INFO

Keywords:
AUV/ROV propulsion design
Autonomous underwater robots
Genetic algorithms
Task-based design
Model-based mobile robot control

ABSTRACT

In this work, a method for the dynamic reconfiguration of autonomous underwater vehicles (AUVs) propulsion system is developed and tested in simulation. Global optimization is used to find suitable propulsive configurations and control parameters in order to achieve successive robotic tasks. This is done using a genetic algorithm used here as a task-based design method. Evaluation of the AUV configuration is made using a dynamic simulation of the robot performing its mission involving a non linear control (computed torque method). The objective function minimizes the trajectory tracking error and the energy consumption. The results of this optimization could be used as a preliminary design step for a specialized AUV, finding the fittest propulsive configuration. Here, we propose the dynamic reconfiguration of a multitasking AUV that adapts its propulsion configuration to the changing task specifications during its mission. The method implementation is based on the dynamic model of an existing AUV (IRDL-RSM 4-fixed thrusters under-actuated robot), but searching for new thrusters directions and controller parameters to perform successive tasks.

1. Introduction

In the second half of the 20th century, thanks to marine technology maturity, marine robotics made its appearance in ocean exploration. Namely, Unmanned Underwater Vehicles (UUVs) started being developed and since then, as noted in Antonelli (2006), advancements in technology allowed to have a rapid progression in their capabilities. Nowadays, UUVs have become increasingly prevalent and are used for scientific, military, and industrial purposes. Current UUVs capabilities allow to perform tasks not even imaginable fifty years ago, see McPhail (2009), Ribas et al. (2015) and Bruno et al. (2015). A type of UUV, used to perform missions without human intervention, is called Autonomous Underwater Vehicles (AUVs), which after decades of development have proven the ability to achieve increasingly complex missions. Even if great advances have been accomplished in terms of autonomy, nowadays AUVs have reduced maneuverability, as noted in Djapic et al. (2007), Nguyen et al. (2009), Barngrover et al. (2011), Chen et al. (2015) and Li et al. (2015). Enhanced AUV agility (maneuverability and speed) brings increased autonomy. Indeed, current computing processing and sensor technologies allow implementing sophisticated model-based control methods. These advances added to developments in propulsion technology, would increase AUVs agility if coupled with efficient control.

In this work we focus on the design of propulsion system itself and its efficiency in order to achieve higher agility for autonomous vehicles. We determine here the most suited propulsive configuration for a given task (or subtask). This search includes, in part, the topology (orientation of the thrusters) and the control system (control gains and tracking point position), but not the reconfigurable thrusters technology, nor the issue of transition between configurations. We call this technique 'dynamic reconfiguration of propulsion system', since it can be operated in mission. The method is applied here to a 4-thrusters AUV (namely RSM robot), but is not limited to it. Vectored thrust technology is not discussed in this work, but we have based our models and our method on real vector thrusters that can actually and independently orient their thrust (hence their propeller), as proposed in Vega et al. (2016).

Classical design consists in solving all sub-system design problems independently in a preconceived order, see D'Souza (1998). This method is not adapted for complex robotic systems where no definitive design method is proven. We propose then to adopt a task-based design method, in order to drive the AUV propulsion design process, using evaluation from simulation including control. Taking into account the complexity of designing a robot propulsion, it is clear that such a difficult task would

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https://doi.org/10.1016/j.oceaneng.2018.02.056
Received 25 January 2017; Received in revised form 19 January 2018; Accepted 21 February 2018

greatly benefit from a computer-based search method. Namely, the design problem discussed in this research work, can be formulated as a global optimization problem, similarly as for kinematic design of robotic arms shown in Chocron and Bidaud (1997). Our optimization problem is then, the minimization of an objective function, calculated taking into account the robot global performances while performing a mission (in simulation). Giving the astronomical number of available possible solutions and the lack of uniformity in the design parameters, we can not use classical optimization techniques (gradient based search). In order to solve this optimization problem, we use evolutionary algorithms Holland (1975), which operates the power of artificial evolution to find suitable solutions to our problem. Given that AUVs have an on-board power storage system, it is important that improvements in agility do not increase power consumption beyond measure. This trade-off (agility vs power efficiency) will guide us during the optimization process. Based on their ease of use, the simplicity of their implementation and their applicability, genetic algorithms will be used to solve the design problem in this work. Indeed, task-based propulsive solutions will be created taking the AUV design as an optimization solved with genetic algorithms, as in Chocron (2008).

This work is organized in five additional sections prior to conclusion. Section 2 presents dynamic models of our reference RSM-like AUV (RSM robot but with vectored thrusters) and its propulsion systems. Section 3 proposes a nonlinear model-based control method, namely computed torque control. Section 4 deals with the thrust generation applied to any RSM-like AUV. Section 5 details our original application of genetic algorithms to the dynamic reconfiguration of AUV propulsion problem. Section 6 shows the results of the genetic optimization applied to a threefold realistic mission consisting of a marine tidal turbine inspection.

2. AUV dynamics modeling

In order to evaluate the pertinence of the found solutions, the genetic algorithm needs an evaluation method. In our case, the evaluation will be done by dynamic simulation, even if other methods exist, see Koos et al. (2013). Our choice is based on the fact that our simulator (EAUVIVE[1]) introduced in Vega et al. (2014), even if approximated (lacking of fluid mechanics and experimental validation of added mass terms), offers an acceptable degree of relevancy considering our goal: finding solutions that could aid to the design of underwater robots propulsion.

The EAUVIVE simulator, described in Vega et al. (2014), includes a model of the AUV rigid body dynamics, hydrodynamic effects, a model-based control method, a thrust allocation method, and a nonlinear model of the force generated by the thrusters.

2.1. Kinematic model

To model the AUV, two orthogonal coordinate systems are used: R_0 ($O_0, \mathbf{x}_0\mathbf{y}_0, \mathbf{z}_0$) is the earth-fixed frame and R_b ($O_b, \mathbf{x}_b, \mathbf{y}_b, \mathbf{z}_b$) is AUV body-fixed. In Fig. 1, body-fixed, and earth-fixed coordinate systems are shown together with a diagram of the AUV.

The vectors describing the motion of the AUV in 6 DOF are:

$$\boldsymbol{\eta} = \begin{bmatrix}\boldsymbol{\eta}_1\\ \boldsymbol{\eta}_2\end{bmatrix} \boldsymbol{\eta}_1 = \begin{bmatrix}x\\ y\\ z\end{bmatrix} \boldsymbol{\eta}_2 = \begin{bmatrix}\phi\\ \theta\\ \psi\end{bmatrix}$$
$$\boldsymbol{\nu} = \begin{bmatrix}\boldsymbol{\nu}_1\\ \boldsymbol{\nu}_2\end{bmatrix} \boldsymbol{\nu}_1 = \begin{bmatrix}u\\ v\\ w\end{bmatrix} \boldsymbol{\nu}_2 = \begin{bmatrix}p\\ q\\ r\end{bmatrix} \quad (1)$$
$$\boldsymbol{\tau} = \begin{bmatrix}\boldsymbol{\tau}_1\\ \boldsymbol{\tau}_2\end{bmatrix} \boldsymbol{\tau}_1 = \begin{bmatrix}X\\ Y\\ Z\end{bmatrix} \boldsymbol{\tau}_2 = \begin{bmatrix}K\\ M\\ N\end{bmatrix}$$

Here $\boldsymbol{\eta}$ is the vector of position and orientation in R_0. The orientation

[1] ENIB AUV In Virtuo Experiment, IRDL-ENIB 2007–2017.

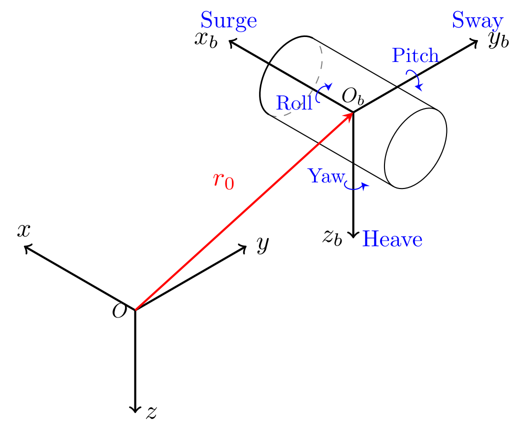

Fig. 1. Earth-fixed and body-fixed frames.

$\boldsymbol{\eta}_2$ is defined using an Euler ZYX (ψ, θ, ϕ) convention as described in Fossen (1994). $\boldsymbol{\nu}$ is the linear and angular absolute velocity vector in R_b. $\boldsymbol{\tau}$ is the external forces and moments vector in the body-fixed frame, which accounts for propulsion forces applied on the AUV. Precisely, this vector will allow modeling thrust forces from different propulsion architectures.

To change the AUV velocity vector from one to another coordinate system we use a velocity transformation matrix as given in Fossen (1994):

$$\mathbf{J}(\boldsymbol{\eta}_2) = \begin{bmatrix}\mathbf{J}_1(\boldsymbol{\eta}_2) & 0_{3\times3}\\ 0_{3\times3} & \mathbf{J}_2(\boldsymbol{\eta}_2)\end{bmatrix} \quad (2)$$

Where,

$$\mathbf{J}_1(\boldsymbol{\eta}_2) = \begin{bmatrix}c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta\\ s\psi c\theta & c\psi c\phi + s\theta s\theta s\psi & -c\psi s\phi + s\theta s\psi c\phi\\ -s\theta & c\theta s\phi & c\theta c\phi\end{bmatrix} \quad (3)$$

and

$$\mathbf{J}_2(\boldsymbol{\eta}_2) = \begin{bmatrix}1 & s\phi t\theta & c\phi t\theta\\ 0 & c\phi & -s\phi\\ 0 & \frac{s\phi}{c\theta} & \frac{c\phi}{c\theta}\end{bmatrix}$$

Using this transformation matrix, we can obtain the AUV absolute velocity vector expressed in R_0 from its expression in R_b, see Fossen (1994):

$$\dot{\boldsymbol{\eta}} = \frac{d\boldsymbol{\eta}}{dt}|_{R_0} = \mathbf{J}(\boldsymbol{\eta}_2)\,\boldsymbol{\nu} \quad (4)$$

2.2. Dynamic model

The nonlinear rigid-body dynamic equations of the underwater robot, can be formulated as in Antonelli (2006) and Fossen (1994):

$$\mathbf{M}\,\dot{\boldsymbol{\nu}} + \mathbf{C}\,\boldsymbol{\nu} + \mathbf{D}\,\boldsymbol{\nu} + \mathbf{G} = \boldsymbol{\tau} \quad (5)$$

where $\mathbf{M} \in IR^{6\times6}$, $\mathbf{C} \in IR^{6\times6}$ and $\mathbf{D} \in IR^{6\times6}$ are the matrices of mass, Coriolis and centripetal terms, and damping respectively (including added mass terms). $\mathbf{G}$ is the vector of gravitational forces and moments. Lastly, $\boldsymbol{\tau}$ is the wrench of external forces and moments.

The wrench $\boldsymbol{\tau}$, accounts for the propulsive forces generated by the thrusters. It is calculated as follows:

$$\boldsymbol{\tau} = \mathbf{B}_p\,\mathbf{u}_p \quad (6)$$

where $\mathbf{B}_p$ is the thrust control matrix (TCM), which depends on the propulsive configuration (number, position and orientation) of the actuators. $\mathbf{u}_p$ is the vector of the actuators forces (i.e., thrust output).